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**CALIBRATION AND CHARACTERIZATION
OF YTTERBIUM STRESS TRANSDUCERS**

Final Report - Task III

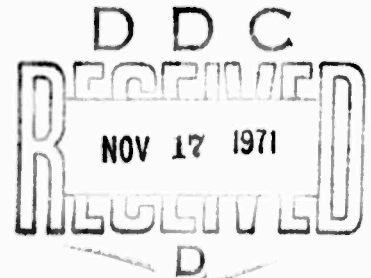
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13. ABSTRACT A series of experiments at stress levels up to 7.8 kbar were performed to determine the resistance change at peak dynamic stress of four-terminal gages fabricated from ytterbium foil and encapsulated in plexiglas. Four different lots of 99.9% pure ytterbium obtained from a single supplier were used in the experiments. There was an apparent difference in response to loading between one lot of foil and the response of the other three taken together, and it proved to be significant when tested statistically. However, given the accuracy levels now considered acceptable in field measurements, we have concluded that this difference would be insufficient to cause important differences in peak stress values derived from the resistance changes measured in subsequent experiments. Therefore, if a lot of ytterbium foil meets the tentative specifications suggested in this report, it should be suitable for use as a gage material for peak stress measurements. The stress-resistance paths during release were nonlinear, deviated from the loading curve and did not return to zero resistance change at zero stress. The data were obtained by comparing gage records with stress-time histories generated by a modified SWAP-7 computer code using plexiglas stress-strain data as the input. Because of the approximation involved in the calculations, and the difficulties inherent in the comparison of the gage records and computer output, the release calibration curves should also be considered tentative. Further work is required to improve both the accuracy and the precision of the release calibration.			

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Ytterbium Stress transducer Shock Waves Calibration Metallurgy of Gage materials Release paths Hysteresis Field measurements						

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PREFACE

The author would like to express appreciation to the following individuals who contributed in a meaningful way to the work described in this report: P. DeCarli, J. Hannigan, R. Lucas, R. C. Singleton, D. Erlich, B. Lew, D. Curran, T. Barbee, D. D. Keough, D. Grine, L. Seaman, A. Urweider, J. Yost, J.T. Rosenberg, J. Dempster, G. Cartwright, and W. Murri.

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I INTRODUCTION

The work reported here was designed to provide a more accurate calibration of the stress-resistance behavior of ytterbium in loading and unloading and to determine whether or not differences in chemical purity and metallurgical history among lots of commercially available ytterbium cause important differences in the piezoresistance^{*} coefficient. Previous work by Keough (1970) demonstrated that ytterbium is a promising material for use as a high sensitivity element in a piezoresistant stress gage.

The previous calibration of the stress-resistance behavior of ytterbium was not sufficiently complete, particularly for stresses below 10 kilobars. Moreover, no investigation has been done on the effects of differences in composition and mechanical history of different factory lots of ytterbium on their stress-resistance behavior. If such differences between different factory lots should produce important differences in piezoresistance coefficients, each user would have to obtain a large supply of ytterbium, calibrate his supply, and make all his gages from that lot. The difficulty of such a procedure would discourage use of the material and would certainly reduce confidence in any measurements. However, if standards can be set up, this difficulty can be avoided to some extent.

The principal intended use for ytterbium stress gages is in field measurements of stress pulses in rocks and soils over the stress range between 1 and 20 kbar. Under Task II of this project, field gages have been fabricated and emplaced on two nuclear shots--Diamond Mine and Diagonal Line. Adequate stress measurements on such tests are required in experimental studies of coupling of energies from explosive sources into ground shock and seismic waves and of effects of ground shock on structures.

* The use of piezoresistance (as opposed to piezoresistive) is preferred because we are measuring a total resistance change due to a change in resistivity and cross-sectional area rather than a change in resistivity alone.

Field stress measurements in the range of 1 to 20 kbar, for which ytterbium is particularly suited, should help improve the reliability of prediction computations. The stress measurements should be quite useful in checking both computational methods and mathematical models for constitutive relations. On a related DASA contract, we are currently attempting to develop a particle velocity gage suitable for use over the same region in order to permit calculations of the in situ constitutive relations from the combined measurements.

Piezoresistance transducer systems for use in soils and rocks have been developed that use manganin grids embedded in epoxies or, where conditions permit, directly in the soil or rock. These systems have been used in numerous field tests to record stress profiles ranging from a few kilobars to hundreds of kilobars at durations ranging from a few μsec to over 100 μsec . However, the stress-resistance sensitivity of manganin, $\sim 0.24 \times 10^{-2} \Omega/\Omega \text{ kbar}$ at one kbar, is marginally adequate for field measurement of stresses below 10 kbar. In addition, the use of manganin in inhomogeneous media or under divergent flow conditions is difficult because of its relatively high sensitivity to stretch-induced resistance changes.

Standard ground motion gages to measure stress, displacement, particle velocity, or acceleration, such as those described by Flanders (1964), are commonly contained in rigid cannisters and have internal voids. Such gages often crush or become otherwise inoperative at stresses above about 1 kbar. They are also more difficult to make in forms and of materials which permit an optimum impedance match to a given medium. They also suffer from slow dynamic response.

A secondary use for ytterbium is in high sensitivity dynamic stress transducers for laboratory study of shocks in liquids, composites, and rocks. It can also be used for transducers that can be embedded in the test medium and that flow with the medium (Lagrangian transducers). Such transducers cause a minimum disturbance to the stress wave and provide unique measuring capability.

II BACKGROUND

The active element of a piezoresistant stress transducer is usually a wire, foil, or film of some substance whose total resistance changes in a measurable and reproducible manner when the element experiences a stress change.

The total resistance of the active element is given by

$$R = \frac{\rho L}{A}, \quad (1)$$

where

R = resistance in ohms

L = length of element in cm

A = cross-sectional area in cm²
(normal to major current flow direction)

ρ = resistivity in ohm-cm.

Three separate effects contribute to the measured change in resistance of a gage material under dynamic loading. These are: (1) a resistivity change caused by the strain and production of lattice defects, (2) a resistivity change caused by the temperature rise, and (3) a resistance change attributable to the decrease in cross-sectional area experienced by the element. The resistivity of a normal metallic conductor decreases with pressure and increases with temperature. A decrease in cross-sectional area always increases the resistance of the element. Therefore, if we should choose a normal metallic conductor as our gage element, we would have competing effects (pressure versus temperature plus volume change) and the overall measured sensitivity would be small. For example, the commercial magnesium-lithium alloy LA141 (35 at. % Li) has a negative piezoresistive coefficient, but gages fabricated from LA141 show a positive resistance increase of 2.85% when dynamically stressed to 19 kbar, whereas pure lithium shows a 44% increase at 17.5 kbar under the same conditions. The small resistance increase of the alloy (which barely overshadows the decrease in resistivity) is caused by the temperature and area change. To produce larger signals, metals with positive piezoresistive coefficients (manganin, lithium, ytterbium, and the like) are usually chosen for dynamic stress gages.

Although transducer systems now in use respond accurately under conditions of rising stress, they do not, in general, accurately follow the decay of a stress pulse. Hysteresis, including a change in the zero-pressure resistance and a change in the piezoresistance coefficient, is frequently observed in all of the transducer systems now used. It constitutes a serious limitation to the use of piezoresistant stress transducers, since increasingly accurate measurements of stress wave decay are becoming necessary. For example, such measurements are essential as both input and corrective feedback to computer calculations of stress wave propagation and of stress-wave-induced damage. Further improvement of the calculations, which are not yet adequate, depends on greater accuracy of measurement of the behavior of materials during stress release.

III SUMMARY AND CONCLUSIONS

We have determined the change in resistance as a function of peak dynamic stress at selected stress levels up to and including 7.82 kbar for four different lots of nominal 99.9% purity ytterbium obtained from one manufacturer. We have also determined the change in resistance with stress during unloading from peak stress levels of approximately 4, 2.6, and 1.3 kbar.

The ytterbium stress gages used in the experiments were one mil thick and approximately 10 mils wide. They were embedded in plexiglas, a material which has well-established shock properties in the stress range of interest in this program.

Three of the lots of ytterbium were supplied to us in foil form by the manufacturer. This foil had been rolled from as-distilled material. One lot was rolled here at SRI; the starting material in this case was ingot that had been cast from the distilled material.

The lot which had a different metallurgical history also showed some differences in resistivity, hardness, and temperature coefficient to resistance. This lot was also somewhat less pure (0.03 wt % total) than two of the others because of the presence of 0.05 wt % magnesium. In addition, it exhibited a statistically significant difference in its response to compression when compared to the other three lots. Although the difference was statistically significant, we do not believe to be an important difference given the accuracy levels now considered reasonable for practical stress gages. We have concluded therefore, that any of the four lots of ytterbium we have studied and any other lot which meets our preliminary specifications would be suitable for future use. These observations are valid only for the stress range investigated in this program, and when the gage is encapsulated in materials that behave in the same general way as plexiglas under dynamic loading, i.e., most, if not all, polymeric materials.

Considerable hysteresis (deviation from the loading curve) was found to occur during release. The unloading stress-resistance paths were also found to be nonlinear, and a zero-stress residual resistance was shown after release in all instances except where double shock techniques were used; in these latter experiments the zero-stress residual resistance was either zero or very close to zero after the second shock.

The data obtained from the calibration experiments were fitted by an appropriate mathematical expression using goodness of fit and computational ease as criteria for selection of the "best" expression. The values of stress vs. $\Delta R/R_0$ calculated from this function are also tabulated so that gage records can be analyzed to a first approximation by inspection of this table, if preferred.

The major conclusions we have reached, based on analysis of the experiments performed during this investigation, are listed below.

1. The ytterbium foil used in this study can be partially described in the following way:

The resistivity at atmospheric pressure and ambient temperature was between approximately 29 and 35 $\mu\Omega\text{-cm}$

The purity, excluding gaseous impurities, was 99.9% by weight, and no lot had more than 0.05 wt% of any single impurity

The microhardness (Vickers, 2.5g and 5g load) was between approximately 40 and 60.

Foils which can be described as having properties and purity levels which match the above should respond to dynamic stress in the same way as those used in this work.* However, it should be kept in mind that it is possible that a given lot of ytterbium could have this same set of properties and not respond to dynamic loading in the same way. This is because we have not yet established to what extent the hardness and resistivity values are a function of purity, as opposed to metallurgical history.

2. The peak stress-resistance response of ytterbium during loading in plexiglas at stress levels up to 7.82 kbar can be predicted (with a confidence derivable from the stated standard deviation) by the following expression.

* Within the quoted error limits.

$$\sigma = 0.922 \left[1 - e^{-52.585 \left(\frac{\Delta R}{R_0} \right)} \right] + 9.812 \left(\frac{\Delta R}{R_0} \right) \quad (2)$$

where σ is the peak stress in the direction of wave propagation in kbar, and $(\Delta R/R_0)$ is the fractional resistance change at peak stress. The standard deviation associated with Eq. (2) is 0.108 kbar.

3. Further work is required to improve both the accuracy and precision of the release calibration. Small errors in the plexiglas equation of state, which might arise, for example, from our lack of knowledge about rate dependence during release, could cause errors in our computer-generated stress-time histories. In addition, we are looking at a situation where the slope of the release portion of the resistance-time record is such that small time increments represent large changes in stress. We suggest, therefore, that the release calibration curves presented in this report should be considered tentative until more experiments can be performed.

Some features of the measured unloading curves do require discussion if they are to be used for interpreting gage records. During unloading from stresses up to at least 4 kbar, the decrease in resistance with stress is small at first, then increases appreciably as zero stress is approached. This type of response tends to locate a large amount of information at the beginning of the release portion of a resistance-time gage record, because small changes in resistance seen at this part of the record can represent large changes in stress. In general, the release portion of the stress-time record could bear little resemblance to that of the original resistance-time record. The release curves obtained in this study have not been fitted to analytical expressions because of the small number of data points on each curve.

Given the information presented above and the attendant precautions, the usefulness of ytterbium gages to measure dynamic stress should continue to increase. Future work should include further investigation of the unloading behavior and the subkilobar loading response. The loading curve should also be extended to stress levels above the maximum used in this work.

IV TECHNICAL DISCUSSION

Ytterbium is a rare earth element whose position in the periodic table lies between thulium and lutetium in the Lanthanide series. Its atomic weight is 173.04, and its atomic number is 70. At 25°C and one atmosphere pressure, the equilibrium crystal structure is face-centered cubic, changing to body-centered cubic at approximately 39.4 kbar (Hall, Barnett, and Merrill, 1963). The resistance of ytterbium increases significantly between atmospheric pressure and the phase change at 39.4 kbar, at which point it decreases abruptly to a value slightly below the original resistance. The maximum resistance change under supposedly hydrostatic pressure conditions has been found to be as much as 23 times the original resistance (Stromberg and Stephens, 1964) and as little as 6 times the original (Stager and Drickamer, 1963), whereas the transition pressure has been determined to be between 37 and 41 kbar.* Other polymorphic changes that have been noted are a face-centered to body-centered cubic transformation at one atmosphere and approximately 798°C (Daane, 1961), and a shear transformation from a face-centered cubic to a close-packed hexagonal structure occurring at one atmosphere and approximately 0°C (Kayser and Soderquist, 1969). In addition to these observations, it has been noted that ytterbium behaves as a semimetal† at pressures up to 11 kbar, an intrinsic semiconductor between 11 and 39 kbar, and a metal above 39 kbar. The large difference between the extremes of the peak resistance values measured by various investigators probably arises from impurity effects at high pressures, and also from the increased effect of non-hydrostatic components of stress on ytterbium in its semi-conducting state above 11 kbar. The sensitivity of semiconductors to shear components of stress is well known. As the investigators who have studied this problem have improved their techniques, they have obtained resistance values at the transition stress are in the range of 7-9 times the original resistance.

* This discrepancy might well be due to calibration errors rather than to differences in the ytterbium. The 41-kbar value (Bridgman, 1954) is a corrected figure.

† A semimetal is a substance whose electronic properties lie somewhere between those of a metal and a semiconductor, or which might have features associated with one or the other without showing all aspects of the behavior of either one.

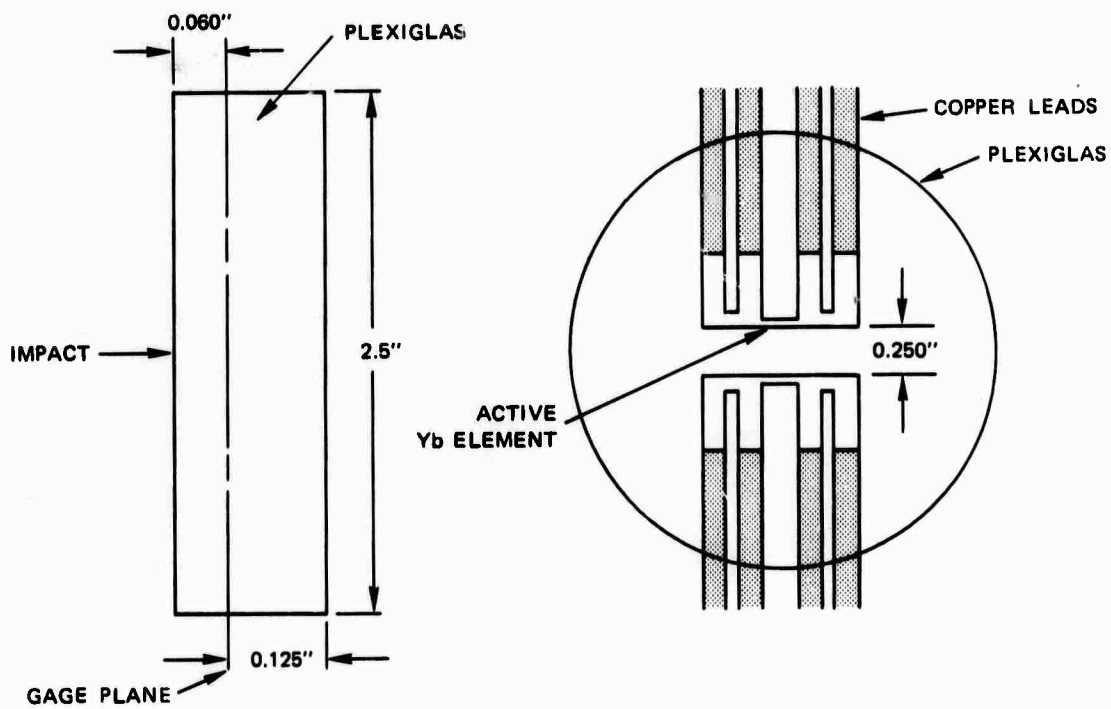
It is not surprising that a substance which displays such complex behavior has attracted increasing attention from both experimentalists and theoreticians in recent years. On the other hand, the high piezo-resistance coefficient (compared to expected resistance changes which might occur during stretching in nonplanar flow conditions) has aroused a more practical interest in the properties of ytterbium because of its attractiveness for use as a quantitative dynamic stress sensor, especially in the low and subkilobar region. Development programs have been recently carried out at SRI (Keough, 1970; Williams, 1970), and ytterbium gages have been used in laboratory experiments (Erlach and Crewdson, 1970) and in small-scale field experiments as another part of this project. The following sections of this report describe the technical aspects of a program that is designed to (a) obtain a quantitative measure of the resistance change of ytterbium as a function of dynamic stress under certain well controlled conditions, and (b) start to investigate the questions that arise about the stress-resistance response of a material that behaves as unconventionally as ytterbium.

The target design for the experiments described in this report is shown in Figure 1. Figure 2 is a photograph of a target which has been instrumented and mounted in the SRI 2.5-inch light gas gun. Each target contained two four-terminal ytterbium gages in one plane located 0.060 inch from the impact surface, and the free surface was 0.125 inch behind the gage plane. The gage thickness was nominally 0.001 inch and the width 0.010 inch; the gages were cut from foil sheets rather than etched. Lateral dimensions of the target were chosen so that the flow in the region of the active elements of the gages was one-dimensional over the entire recording time. The instrumentation and power supply circuitry has been described by Keough (1970).

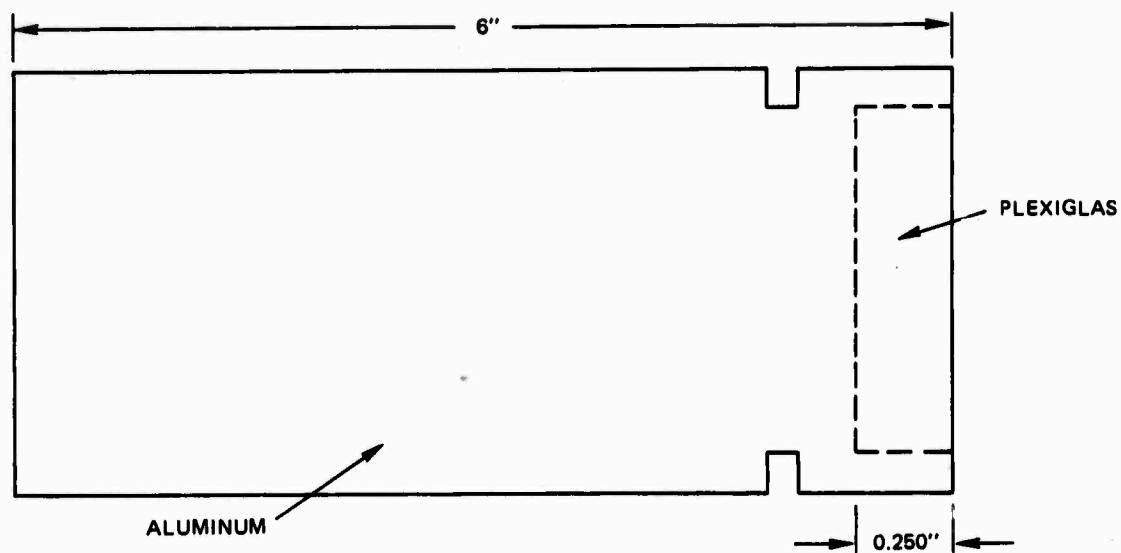
The targets were fabricated from Type II UVA plexiglas,^{*} which has been well characterized (Barker and Hollenbach, 1970). Homalite[†] epoxy, which provides a good impedance match to the plexiglas, was used for all adhesive applications, and the as-received plexiglas surface was used without further milling or surface preparation.

* Trade name, Rohm and Haas, Inc., Pennsylvania.

† Trade name, Homalite Corp., Delaware



(a) TARGET



(b) PROJECTILE

GA-7511-23

FIGURE 1 TARGET AND PROJECTILE FOR GAS GUN EXPERIMENTS

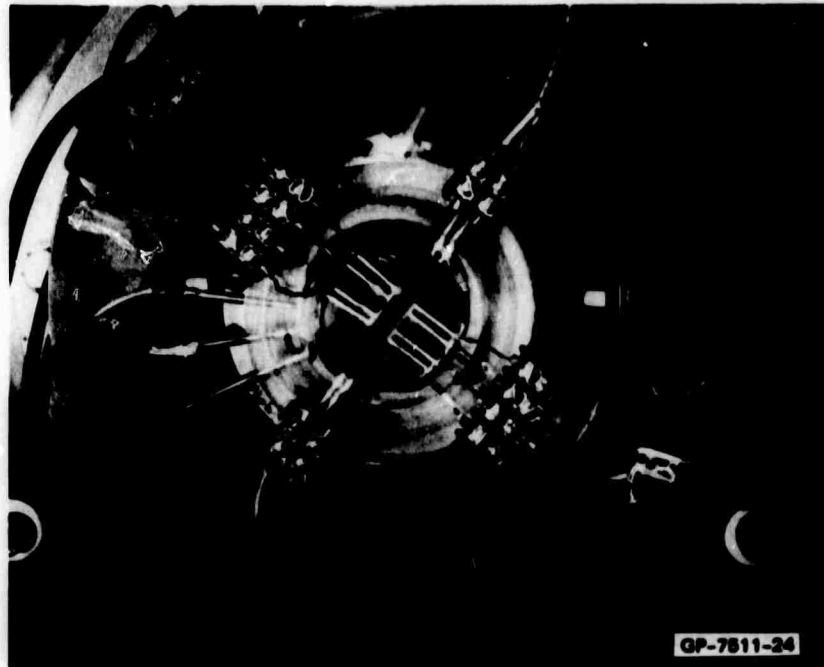


FIGURE 2 TARGET MOUNTED IN GAS GUN

Copper foil gage leads (0.001 inch thick) were soldered to the ytterbium with an indium base solder. Careful mechanical cleaning of the ytterbium surfaces immediately before soldering was necessary to avoid poor adhesion at the solder joint. Poor adhesion is usually caused by the presence of a porous ytterbium oxide film on the gage surface. In some cases poor adhesion can also arise from the formation of an intermetallic compound at the interface which is brittle, or which has a significantly different volume than either the ytterbium or the solder. Deterioration of a solder joint was detectable before a shot when the gage was pulsed to obtain a baseline resistance. A drop in the resistance with time during the pulsing usually signified a poor joint on one of the voltage leads. Occasionally, the resistance would be constant during the pulse but would show a slightly different value if pulsed again. It is difficult to interpret this, but fortunately, the resistance would approach some equilibrium value with continued pulsing, and the gage operated properly when loaded. Out of the total of 24 ytterbium gages fabricated and shocked during this project, only two failed. One failed before the shot,

and another during loading. Each had shown the decrease in resistance with time we attribute to a faulty voltage lead. We are continuing work on the lead-attachment problem and expect to be able to produce gages that have practically zero probability of failure because of the leads.

The power supply and the slow-sweeping oscilloscopes ($2 \mu\text{sec/cm}$) were triggered when the projectile edge impacted radial pins that were placed at preset distances from the impact plane. Faster sweeping oscilloscopes (less than $1.0 \mu\text{sec/cm}$) were triggered by copper foil contact switches placed on the impact surface. Under normal circumstances, this allowed $0.5 \mu\text{sec}$ between triggering the fast oscilloscopes and the arrival of the stress wave at the gage plane. We used a constant current power supply and assumed in all cases that the change in resistance of a gage was equal to the voltage change recorded by the oscilloscope (i.e., $\Delta R/R_0 = \Delta V/V_0$). Data were read directly from the oscillograms with a Whittaker Telecordex counter. The output was fed into a keypunch, and the final data were computer-plotted using the cards obtained from the Telecordex.

The projectiles were six inches long and were fabricated from 6061-T6 aluminum alloy. The heads (0.250 inches thick) were made from the same plexiglas as the targets (so that we had symmetrical impact conditions), and were set into a recess bored out of the front of the projectile, as shown in Figure 1. This particular arrangement allows us to obtain two data points from our low stress shots. Figures 3 and 4 are schematic diagrams indicating how this is done.

The first stress waves after impact travel into the target and also back into the projectile head. These waves are designated shock (1) in Figure 3, and the magnitude of the stress in both the target and projectile head is determined by the velocity of the projectile and the known shock response of the plexiglas. This stress is also that associated with state 1 in Figure 4, and it gives rise to the first increase in resistance seen in a typical gage record from an experiment of the type (see Figure 5). When this first wave reaches the free surface of the target, a rarefaction wave starts back through the target to the gage, causing the stress in the gage to go to zero. This process is represented in Figure 3 by the intersections of rarefaction (1) with the gage plane, and the stress-particle

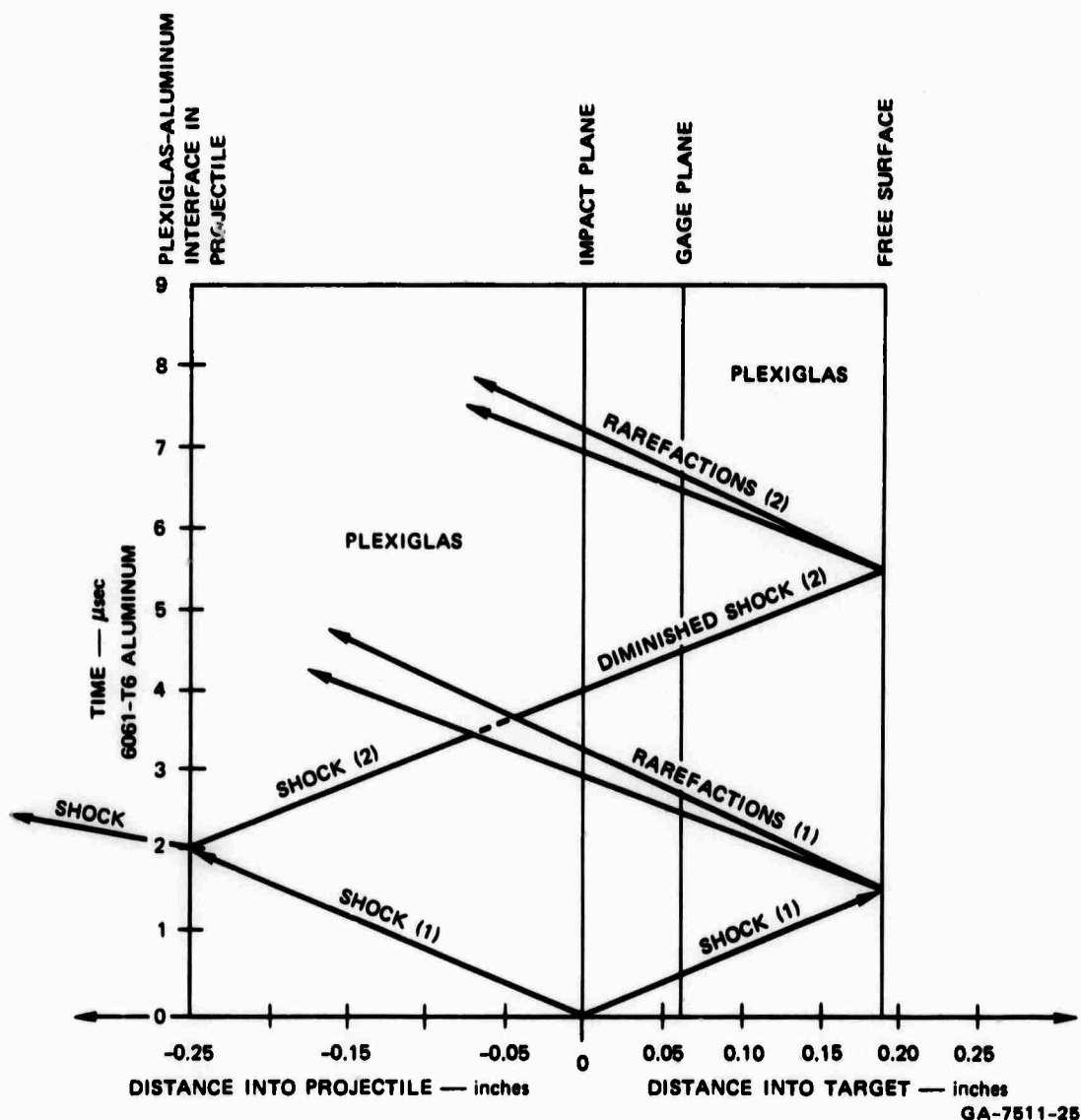


FIGURE 3 SCHEMATIC DIAGRAM OF WAVE INTERACTIONS IN DOUBLE SHOCK EXPERIMENTS

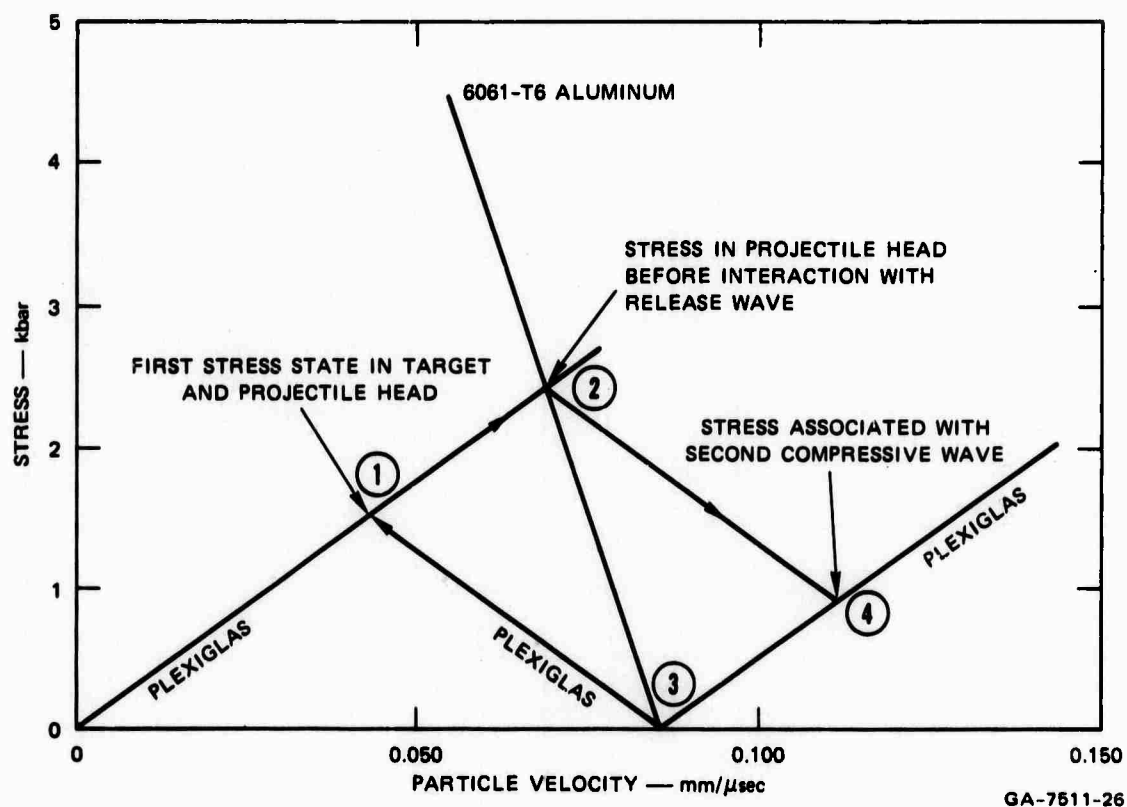


FIGURE 4 SCHEMATIC DIAGRAM OF IMPEDANCE MATCHING TECHNIQUE FOR DETERMINATION OF STRESS ASSOCIATED WITH SECOND COMPRESSIVE PULSE

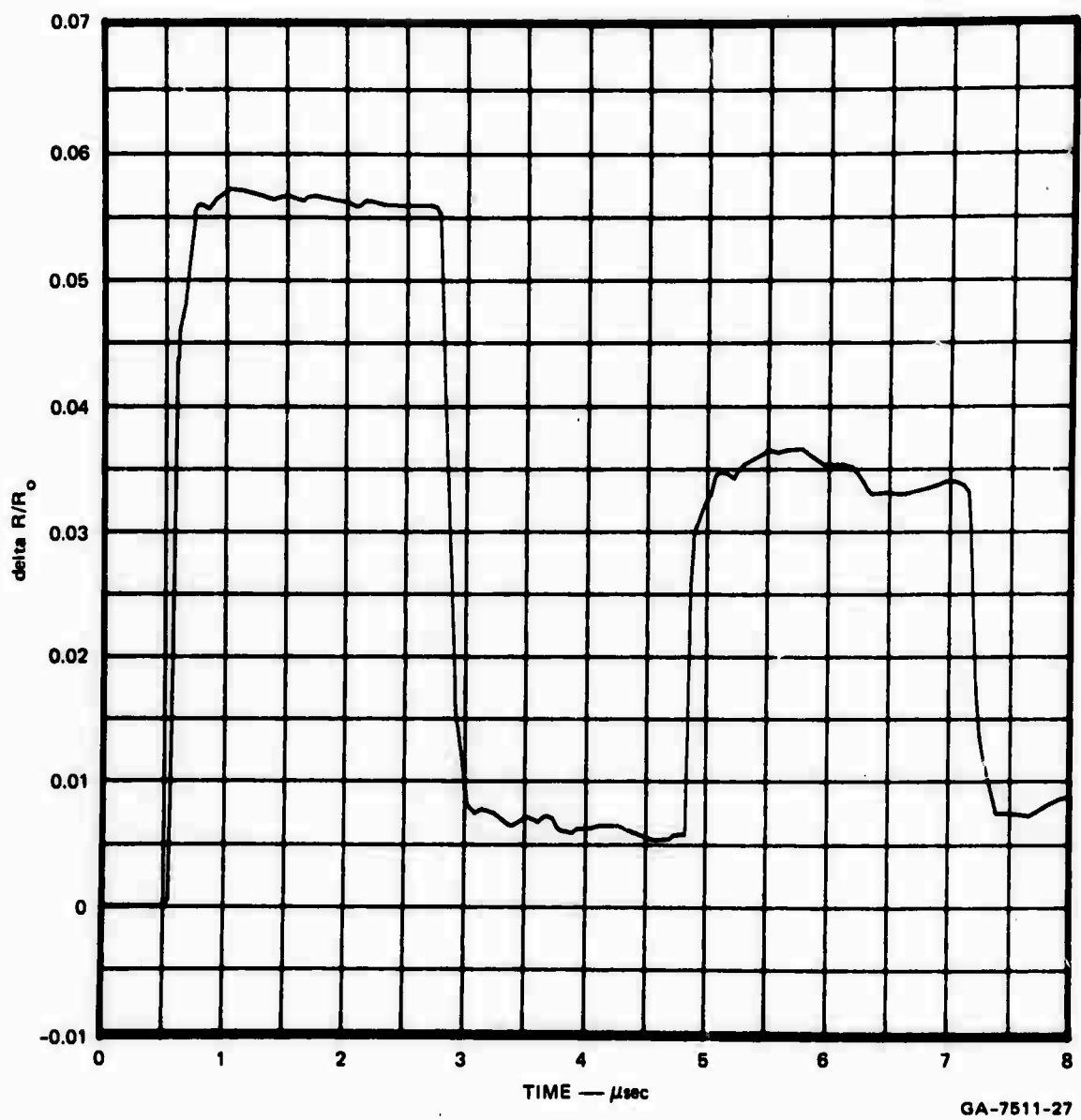


FIGURE 5 REPRESENTATIVE GAGE RECORD SHOWING RELOADING

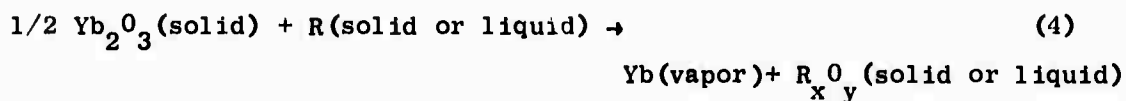
velocity state in the target is now located at point 3 on Figure 4. During the time that the gage has undergone its first loading and release, the wave that has traveled back into the plexiglas projectile head interacts with the higher-impedance aluminum behind it, and a compression wave-- shock (2)--now moves back into the projectile head toward the target. This process is represented by going from point 1 to point 2 on Figure 4, and the stress associated with this wave is the stress at point 2 in that figure. Before this wave reaches the gage plane, it interacts with the rarefaction that had originated at the free surface of the target, and the stress associated with the wave moving toward the gage is reduced by an amount which can be obtained from Figure 4 by moving from state 2 to state 4, which represents what happens to the plexiglas in the projectile head during this interaction process. The gage plane in the target, which is in state 3, subsequently sees this wave, referred to as diminished shock 2 on Figure 3, and moves from point 3 on Figure 4 to point 4, where it stays until the stress is again reduced to zero by rarefactions originating at the rear free surface of the target, and the experiment is terminated shortly thereafter by release waves coming in from the sides of the target.

In this project we have limited this technique to use below initial stress of 1.5 kbar. Double shocking has been used previously (e.g., Keough, et al., 1968) to gain additional data, but the experiments have always been designed so that the second peak was of equal or higher stress than the first.

The side-by-side gage emplacement configuration was chosen because it provided at least two calibration points from each shot, and also because it allowed us to compare records directly from the same experiment, giving us a better indication of reproducibility levels. In addition, this arrangement gave an indication of the amount of shock tilt present along the axis perpendicular to the sensitive elements during the experiment. If arrival time for one gage differs appreciably from that of the other, then we know that appreciable tilt was present. This was not noted in any of our shots. The measured rise times, which were always less than 50 nanoseconds, confirm the absence of substantial shock tilt parallel to the gage elements.

A. Characterization of Ytterbium

Ytterbium metal is obtained by mixing its oxide (Yb_2O_3) with a reducing agent such as calcium, silicon, aluminum, or magnesium (or a combination of these metals) and heating the mixture in a vacuum. The oxide reacts with the reducing agent, and under the proper conditions the reaction



goes strongly to the right. The ytterbium vapor is condensed on a cold collector placed above the crucible.

The metal obtained from this process is often purified further by redistillation under vacuum, and the final product is called distilled lump. This lump can be rolled directly into foil, or it can be remelted, cast into ingot, and then rolled into foil. Three of the foil lots used in this work were rolled from distilled lump by the supplier,* and one lot (068) was rolled to foil at SRI from cast ingot. All of the material was of nominal 99.9% purity. The spectrographic analyses supplied by the manufacturer are given in Table 1. There is little difference between lots 094D and 095D (50 ppm of manganese[†]) and the major chemical differences between these two lots and the other two are the presence of 500 ppm of yttrium in lot 064D and 500 ppm of magnesium in lot 068. This purity level is about the same as that of the material used by all of the investigators who have previously studied the static pressure-resistance response of ytterbium (Jerome, Rieux, and Achard, 1970; Hall, Barnett, and Merrill, 1963; King and Harris, 1970; Souers and Jura, 1963; Lilley and Stephens, 1971 and Bridgman, 1954) and also by those who have studied dynamic behavior (Keough, 1970; Brown, 1970).^{**}

* Research Chemicals, Inc., Phoenix, Arizona.

† 1 ppm = 10^{-4} wt %.

** Keough's ytterbium was the material designated 064D and subsequently used in the present work.

Table 1
SPECTROGRAPHIC ANALYSES OF YTTERBIUM FOIL
(All Values in ppm by Weight)

<u>Impurity</u>	<u>Lot Number</u>			
	<u>094D</u>	<u>095D</u>	<u>064D</u>	<u>068</u>
Lutetium	<50	<50	<50	<50
Thulium	<50	<50	<10	<50
Erbium	<50	<50	<50	<50
Yttrium	<50	<50	500	<50
Dysprosium	<50	<50	<50	<50
Silicon	<100	<100	<50	<100
Magnesium	<100	<100	100	500
Calcium	<100	<100	100	<100
Aluminum	<100	<100	<50	<100
Iron	<100	<100	<100	<100
Tantalum	n.d.	n.d.	n.d.	n.d.
Manganese	50	n.d.	n.d.	n.d.
Purity	>99.92%	>99.92%	>99.89%	>99.89%

< = less than
> = greater than
n.d. = not detected

Instead of determining the chemical composition of the material by electron microprobe analysis or an equivalent technique, we chose to use the spectroscopic analysis supplied by the manufacturer. If the piezo-resistant response was so sensitive to impurities that truly important differences could be noted among different batches of nominally 99.9% pure material which have similar mechanical history, then the utility of ytterbium in this application would be seriously compromised. We repeat here that the objective of this work was not to determine the effect of specific impurities on the piezoresistance coefficient of ytterbium, but rather to determine whether or not there were large differences among batches of the commercially pure material which is now available.

Three types of characterization experiments were chosen to supplement the information available on chemical purity. These were (1) determination of the original resistivity (ρ) of each lot of foil at ambient temperature and pressure, (2) determination of the variation of resistance with temperature, and (3) determination of hardness (an indication of mechanical and thermal history).^{*} In addition, we attempted to perform metallographic examination of the foils, but the absence of preexisting information on specimen preparation, etching, and normal ytterbium microstructure along with the difficulty in handling the thin foils made this task more difficult than expected, and we decided that this task should be postponed.

Resistivity values, given in Table 2, were obtained by determining the dimensions of strips of foil approximately two inches long, attaching the strips to glass substrates, and measuring their resistance with a Kelvin double Bridge. Current was supplied through two leads on the ends of the strip, and the resistance values were read between two inner terminals. This four-lead measurement system helps to eliminate the effect of contact resistances because no current flows in the actual measuring loop.

* All three of these parameters can, however, depend on chemical purity as well as metallurgical history. Specific identification of cause and effect could not be attempted within the scope of the present program.

Table 2

ORIGINAL RESISTIVITY OF YTTERBIUM FOIL

<u>Manufacturer's Lot No. Stock</u>	<u>Original Resistivity $\rho \times 10^6 \mu\Omega\text{-cm}$</u>
095D	30.9 ± 1.0
095D	30.1 ± 2.0
094D	29.0 ± 2.2
094D	28.4 ± 2.0
068	34.7 ± 2.5
068	34.7 ± 2.5
064D	30.0 ± 1.8

Resistance as a function of temperature was obtained by immersing the resistivity specimens described above in an oil bath that could be heated to over 100°C and again measuring the resistance with a Kelvin double Bridge. The results are shown in Figure 6. In these experiments our ability to measure the temperature exceeded our ability to control it. Because of this, the results shown in Figure 6 do not start at the same initial temperature and all of the lines must be normalized to a single starting temperature (e.g., 20°C) before any conclusions can be drawn from the data. This normalization was done for the discussion of temperature contributions to piezoresistance response which appears later in this section.

Microhardness measurements were made on two lots of foil using a diamond pyramid indenter and a Bergsman microhardness tester. The thinness of the foil and the inherent softness of the ytterbium again caused experimental difficulties, but relative values could be obtained for lots 094D and 068. The results are presented in Table 3.

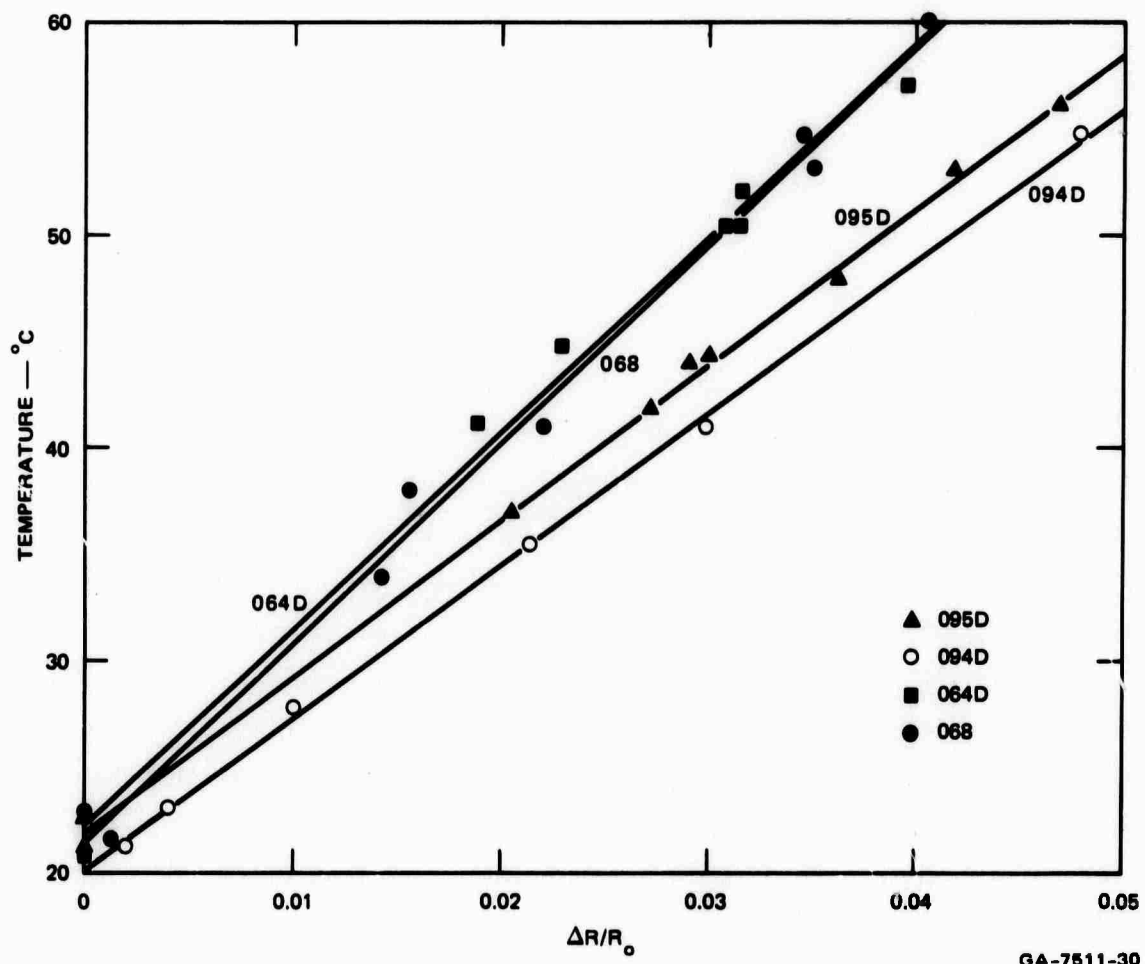


FIGURE 6 RESISTANCE CHANGE OF YTTERBIUM AS A FUNCTION OF TEMPERATURE

Table 3

HARDNESS OF YTTERBIUM FOIL

<u>Manufacturer's Lot No.</u>	<u>Vickers Microhardness Number (5-g and 2.5-g load)</u>
094D	Approx 40
068	Approx 60
"Book Value " for annealed Yb (Simons, 1967)	Approx 20

B. Results and Discussion

In the discussion that follows, differences between or among gage readings, or between measured and predicted values of stress will be expressed in three different ways and clearly identified: (1) in terms of percent of peak $\Delta R/R_0$ with the denominator chosen to be the larger of the two values of $\Delta R/R_0$ obtained in the experiments; (2) in terms of percent of R_0 , which is slightly more convenient to relate to stress; and (3) in terms of the absolute and percentage stress difference that would be obtained in the particular situation being described, using the larger value of stress as the denominator. The error in the computed difference which arises from the errors associated with each individual reading will not be included because it adds little information to the overall result, and is usually quite small.

The results of the dynamic stress experiments are summarized in Tables 4, 5, and 6, and Figures 7 through 10. Inspection of a plot of the loading data points suggested use of a calibration curve of the form

$$\sigma = A(1 - e^{-Cx}) + B \quad \text{for } x \geq 0, \quad (5)$$

where $x = \Delta R/R_0$. The method used was to search for a value of C that minimized the residual sum of squares, using a least-squares solution for A and B at each step. When the full set of 29 data points was fitted, a standard deviation of 0.108 kbar was obtained, assuming 3 degrees of freedom for the three coefficients fitted.

Table 4
SHOT SUMMARY

Shot #	Projectile Velocity mm/sec	Particle Velocity mm/sec	Stress ^a kbar	Gage 1 Lot #	$\Delta R/R_0$	Reload $\Delta R/R_0$	Residual R $\Delta R/R_0$	Gage 2 Lot #	$\Delta R/R_0$	Reload $\Delta R/R_0$	Residual R $\Delta R/R_0$	Reload Stress ^a kbar
S2	0.1492	0.0749	2.58	0940	0.1673 ± 0.0001	---	0.0397 ± 0.0012	0950	0.1711 ± 0.0008	---	0.0479 ± 0.0009	---
S3	.0762	.0381	1.32	0950	.0528 ± 0.0003	0.0196 ± 0.0006	.0050 ± 0.0010	0950	.0490 ± 0.0006	0.0229 ± 0.0008	.0039 ± 0.0003	0.78
S4	.0741	.0370	1.28	0940	.0455 ± 0.0002	.0160 ± 0.0005	.0063 ± 0.0003	0940	---	---	---	.77
S5	.0787	.0394	1.35	0640	.0521 ± 0.0003	.0208 ± 0.0006	.0050 ± 0.0010	0640	.0610 ± 0.0010	.0218 ± 0.0010	.0050 ± 0.0010	.79
S6	.0859	.0430	1.50	068	.0565 ± 0.0004	.0225 ± 0.0010	.0060 ± 0.0004	068	.0567 ± 0.0007	.0260 ± 0.0002	.0051 ± 0.0002	.90
S7	.1518	.0759	2.62	068	.1502 ± 0.0002	---	.0321 ± 0.0060	0940	.1721 ± 0.0004	---	.0450 ± 0.0090	---
S8	.1500	.0750	2.60	0640	.1833 ± 0.0001	---	.0402 ± 0.0100	0950	.1823 ± 0.0003	---	.0503 ± 0.0100	---
S9	.2300	.1150	4.02	068	.2991 ± 0.0006	---	.0731 ± 0.0010	0940	.3373 ± 0.0018	---	.0821 ± 0.0150	---
S10	.4190	.2095	7.82	0940	.7226 ± 0.0018	---	.1190 ± 0.0200	068	.6923 ± 0.0019	---	.1272 ± 0.0200	---
S11	.2281	.1140	4.00	0950	.3091 ± 0.0007	---	.0738 ± 0.0050	0640	.2995 ± 0.0018	---	.0676 ± 0.0150	---
S12	.4180	.2090	7.82	0950	.6857 ± 0.0012	---	.1252 ± 0.0100	0940	.7122 ± 0.0010	---	.1321 ± 0.0100	---
S15	.1200	.0600	2.03	0940	.1177 ± 0.0007	---	.0191 ± 0.0004	0940	.0980 ± 0.0008	---	.0131 ± 0.0003	---

^a Using stress-particle velocity results of Barker and Hollenbach (1970).

± Values are standard deviations around the mean of the measured peak $\Delta R/R_0$.

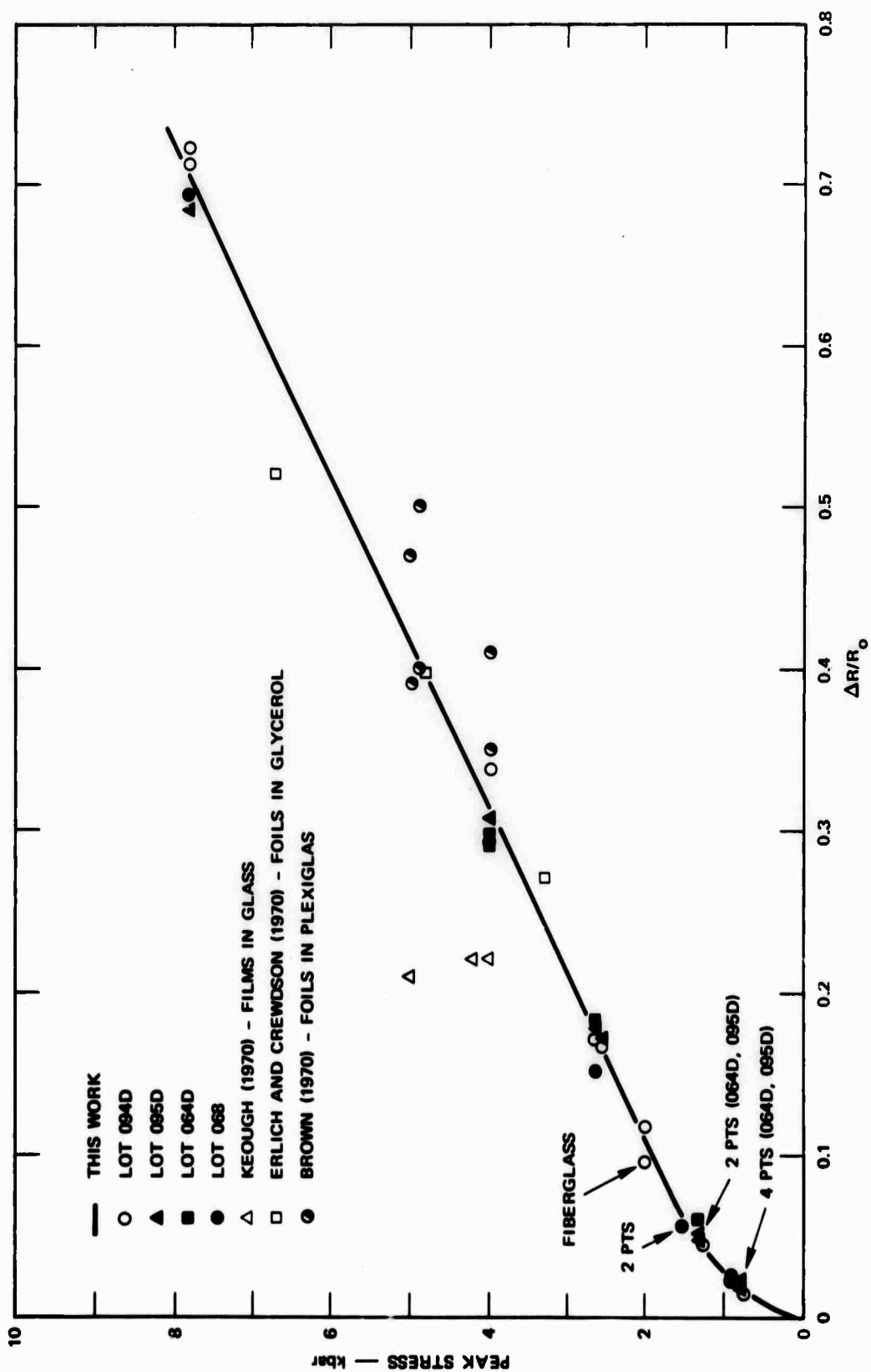
Table 5

Tabulated Values of $\Delta R/R_0$ and Corresponding Peak Stress

<u>$\Delta R/R_0$</u>	<u>Stress (kbar)</u>
0.0000	0.000
.0100	.472
.0200	.796
.0300	1.026
.0400	1.202
.0500	1.346
.0600	1.471
.0700	1.585
.0800	1.693
.0900	1.797
.1000	1.898
.1100	1.998
.1200	2.097
.1300	2.196
.1400	2.295
.1500	2.393
.1600	2.491
.1700	2.590
.1800	2.688
.1900	2.786
.2000	2.884
.2500	3.375
.3000	3.865
.3500	4.356
.4000	4.846
.4500	5.337
.5000	5.828
.5500	6.318
.6000	6.809
.6500	7.299
.7000	7.790

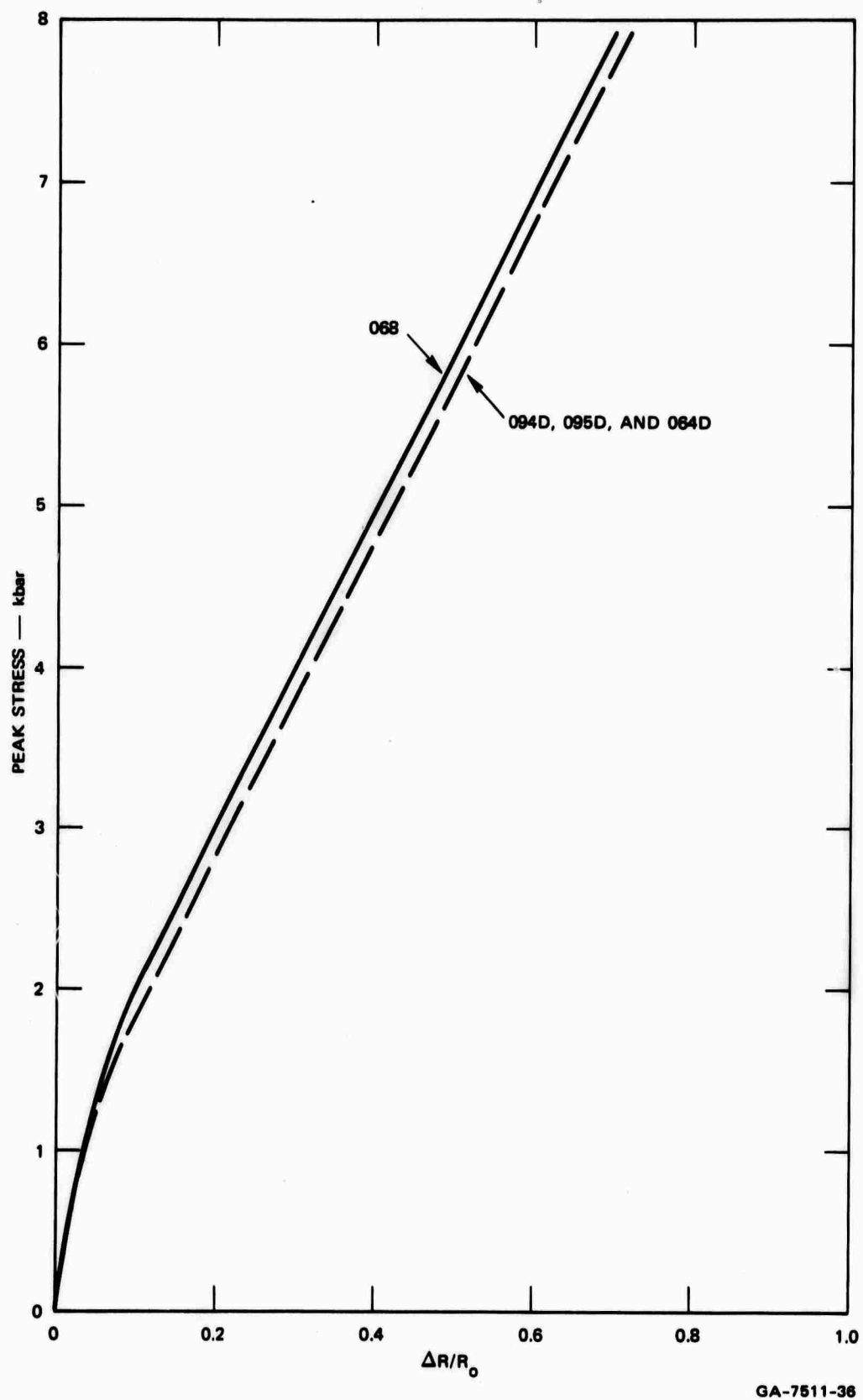
Table 6
UNLOADING CALIBRATION DATA

Shot #	Gage #	Lot #	Stress kbar	$\Delta R/R_o$
S2	1	094D	2.58	0.1673 ± 0.002
			1.018	$.1525 \pm 0.014$
			0.411	$.1180 \pm 0.010$
			0.00	$.0397 \pm 0.006$
S4	1	094D	1.28	$.0455 \pm 0.001$
			1.02	$.0428 \pm 0.023$
			0.398	$.0400 \pm 0.010$
			0.00	$.0073 \pm 0.001$
S9	1	068	4.02	$.2991 \pm 0.003$
			2.63	$.2791 \pm 0.020$
			1.024	$.2399 \pm 0.020$
			0.653	$.1673 \pm 0.048$
S9	2	094D	0.00	$.0730 \pm 0.010$
			4.02	$.3373 \pm 0.011$
			2.63	$.3045 \pm 0.032$
			1.024	$.2451 \pm 0.026$
			0.653	$.1676 \pm 0.045$
			0.00	$.0820 \pm 0.015$



GA-7511-35

FIGURE 7 STRESS VERSUS RESISTANCE CHANGE FOR SHOCK LOADED YTTERBIUM



GA-7511-36

FIGURE 8 FRACTIONAL RESISTANCE CHANGE ($\Delta R/R_0$) AT PEAK DYNAMIC STRESS FOR LOT 068 AND LOTS 094D, 095D, AND 064D

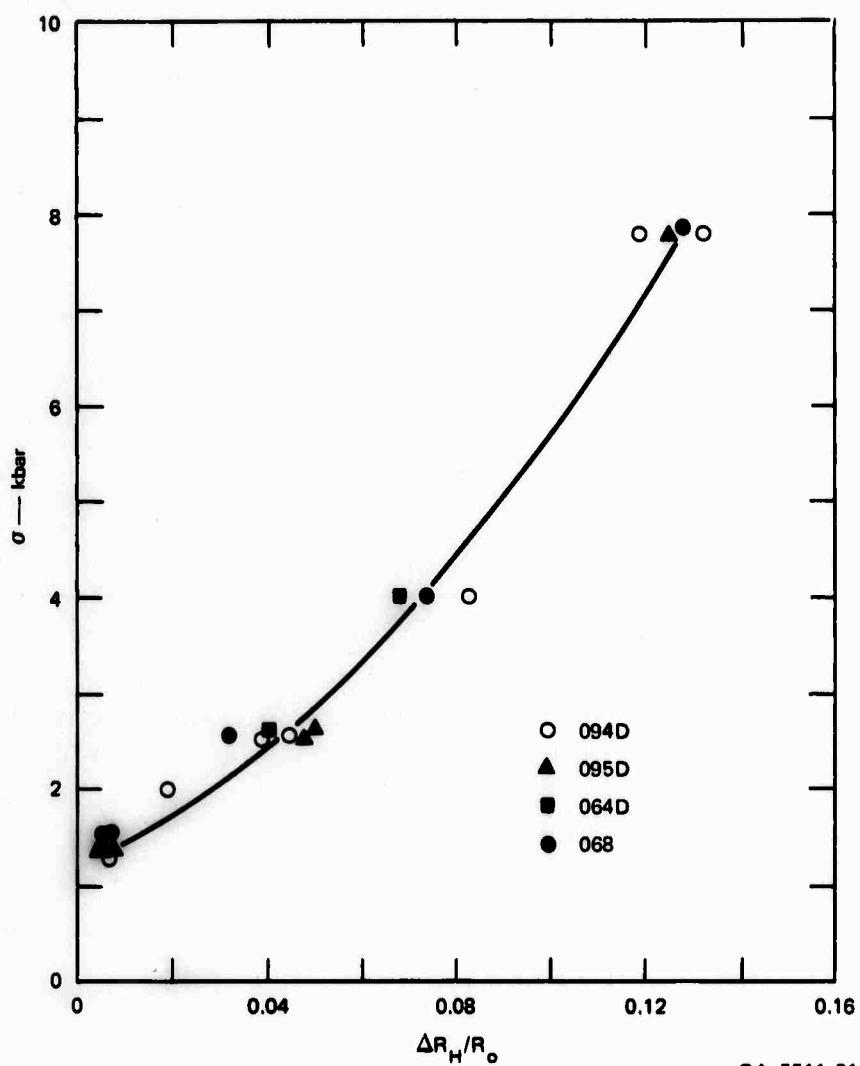


FIGURE 9 ZERO-STRESS RESIDUAL RESISTANCE AS A FRACTION OF ORIGINAL RESISTANCE ($\Delta R_H/R_0$) VERSUS PEAK STRESS

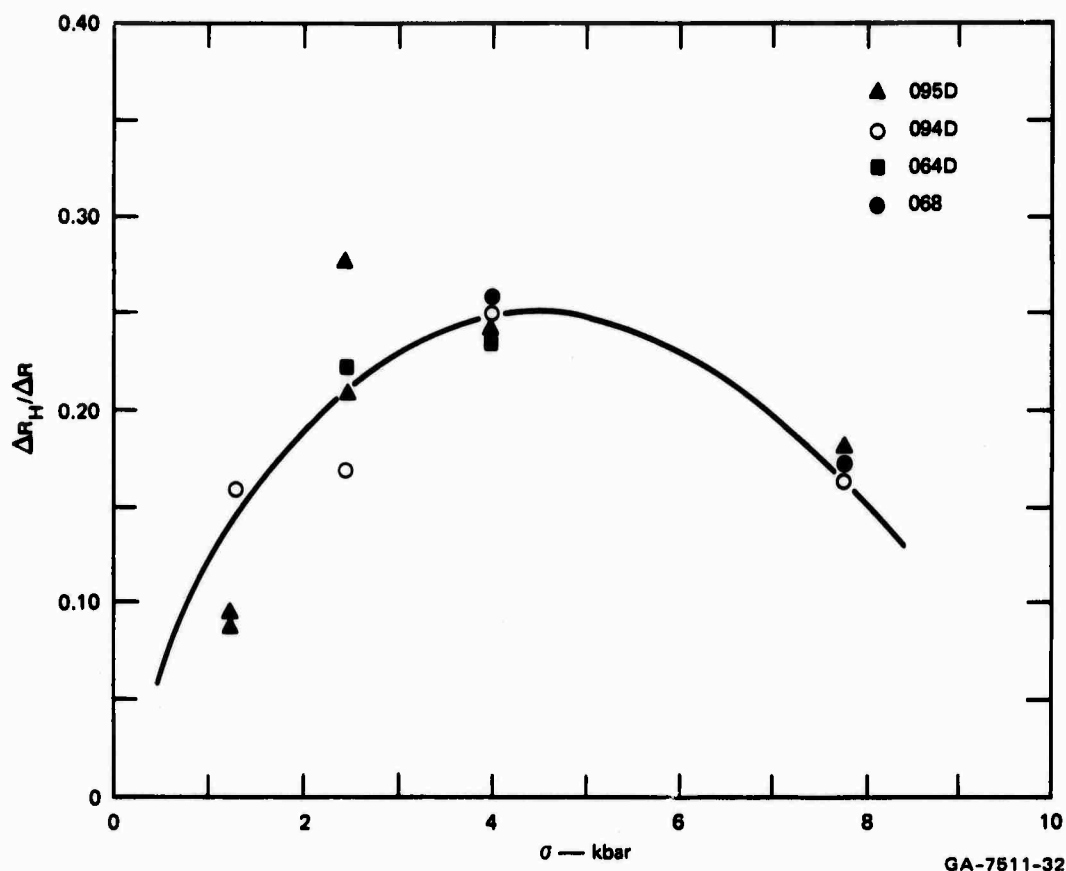


FIGURE 10 ZERO-STRESS RESIDUAL RESISTANCE AS A FRACTION OF MAXIMUM RESISTANCE CHANGE AT PEAK STRESS ($\Delta R_H / \Delta R$) VERSUS PEAK STRESS

Since lot 068 differed from the other three in its manufacturing process, and also in resistivity, hardness and chemical purity, separate calibration curves of the above form were also fitted to the 7 data values for lot 068 (standard deviation 0.044) and to the 22 data values for the remaining three lots (standard deviation 0.097). We did not undertake to ascertain whether or not all four lots differed among themselves in a statistically significant way, nor did we attempt at this time to test any other hypotheses regarding differences among the various lots. Moreover, the standard deviation of the curve through the 22 points (which did not include lot 068) was over twice the standard deviation of the curve associated with lot 068. If it should turn out that single lots always show the least variation, it might be preferable always to use gages fabricated

from the same lot in situations where, for example, measurements are being made in two different places in line in a single event to look at attenuation phenomena. In these cases, small intrinsic differences in response between the gages would be more important than usual, because we are also looking for relative values of stress.

Shot S1, which consisted of four gages in soda-lime glass, did not produce good records because of excessive noise in the recording circuitry. One gage failed on S4 before the shot was fired. Shot S13, which was a step-release (Keough, 1970) experiment specifically designed to produce data on the unloading portion of the stress-resistance curve also failed. In this case one gage ceased to operate before the shot was fired, and the other gage produced a record which contained an unexpected early-arriving signal, possibly arising from polarization of the plexiglas, and the rest of the trace contained no usable information. Shot S14, another release calibration experiment, was canceled when we arrived at another method of obtaining release calibration data.* All of the other experiments were successful, producing a total of 29 peak stress-resistance points† between 0.77 and 7.82 kbar for establishing the ytterbium calibration curve (in plexiglas), plus other valuable information about the dynamic response of ytterbium during loading and unloading.

Shot S2 contained a gage from lot 094D and one from 095D. The peak stress reached was 2.58 kbar and the reloading stress was 1.64 kbar. The reload points were not used for the main calibration curve because we felt that the initial shock could have substantially changed the reloading behavior of the plexiglas and the ytterbium. A residual resistance change ($\Delta R_H/R_0$) or zero-stress hysteresis was noted in this shot, as it was in all of them, but, as has been seen before (Keough, 1970) the further residual resistance change after the second shock approached zero.

* This will be discussed in more detail later in this section.

† Including the origin (0,0).

Shots S3 through S6 each contained two foil gages fabricated from the same lots (but a different lot for each shot). Peak stresses were below 1.5 kbar. Second peak calibration points were obtained using diagrams such as that shown in Figure 4.

Reproducibility between the two gages for the first stress pulse in S3 was approximately 7% of $\Delta R/R_0$, and 0.3% of R_0 , and the stress difference would be about 0.17 kbar or 12%. The corresponding values for the second peak are 15%, 0.35%, and 0.13 kbar or 15% of peak stress. One gage failed in S4, so no comparison is possible. Gage readings in S5 for the first stress pulse differed by about 15% of $\Delta R/R_0$, and 0.9% of R_0 . The stress difference would be approximately 0.1 kbar, or 7%. Corresponding values for the second pulse are 5%, 0.1% and 0.04 kbar or 2.2%. The gage readings from the first pulse in S6 were equal within the precision of our measurements. The second pulse produced records with a difference in $\Delta R/R_0$ of 13% or 0.35% of R_0 , and the difference in stress would be about 0.06 kbar or 7%.

An explanation of the magnitude of the differences in response between two supposedly identical gages under identical loading conditions and the cause of these differences is not apparent. It is possible that small heretofore unidentified differences in fabrication technique could play some part, or that nonlinearities or other effects in the electronic measurement and display systems might enter the picture. Also, it is not inconceivable that variations in material properties could exist in foils from the same lot because of differences in, for example, rolling history between an edge and a center of an ingot. Further investigation of the stress-resistance response in this range, including data on sub-kilobar response to single shocks, would be necessary before a satisfactory explanation can be put forth.

Shots S7 and S8 were performed at the 2.6-kbar level. Each one contained two gages made from two different lots of material. Results were as expected, except that the gage fabricated from lot 068 in S7 displayed what was subsequently seen to be a significant difference in response.

The peak stress for S9 and S11 was chosen to be 4 kbar. All four lots were again investigated in these two shots. The next two, S10 and S12, were shot at 7.8 kbar. Lack of sufficient material from lot 064D restricted us to using gages from the other three lots. The results of S9 and S10 again suggested a smaller resistance change at peak stress for lot 068. Lot 094D, which showed a smaller resistance change than 095D at 2.58 kbar, displayed a greater resistance change than 095D at 7.82 kbar, but the data available are not sufficient to determine whether the difference is random or systematic.

Shot S15 differed from the preceding shots in that one of the gages was sandwiched between two layers of fiberglass,* and the package was placed in the plexiglas next to and in the same plane as a gage that did not have the fiberglass layers around it. This was done so that we could compare the response of the two gages--the fiberglass sandwich configuration being that which we normally use in field work. The difference in resistance change and the difference in stress one would obtain, assuming the two gages are identical and experience the same stress, is 16% of $\Delta R/R_0$, 2% of R_0 , and 0.2 kbar or 10% of peak stress. When we look at the calibration expression, we find that the expected value of stress for $\Delta R/R_0 = 0.117$ is 2.02 kbar and that for $\Delta R/R_0 = 0.980$ is 1.82 kbar. The standard deviation of the calibration curve is 0.108 kbar. Therefore, the difference in stress read with the fiberglass-encapsulated gage is marginally significant at the 5% probability level[†] if we assume that stress equilibrium was reached between the fiberglass and the plexiglas during the measurement time. Since there is no reason to believe that equilibrium was not reached, given the thickness of the gage-fiberglass package (7 mils), we can only conclude that this type of experiment bears repeating so that differences can be more accurately determined and tested for significance.

* "Fiberglass" is used here to designate epoxy reinforced with glass fibers.

† Within two standard deviations of the expected value in this case.

The values of the parameters in Eq. (5) that fitted the experimental data with all points included except the one obtained with the gage in fiberglass are: $A = 0.922$, $B = 9.812$, and $C = 52.585$. The curve obtained through use of this equation is shown in Figure 7, along with the experimental data points from this work and those of other investigators.

These other points were not included in the calibration equations because, for example, Keough used deposited films on soda-lime glass in his below 10-kbar shots. We do not yet know the specific effects of vacuum deposition or of different encapsulants on the dynamic stress-resistance response of ytterbium. This should definitely be a topic for further study. Brown's data are in fair agreement with the present data, but his scatter is somewhat larger. Erlich's values for $\Delta R/R_0$ as a function of peak stress, which were obtained by measuring the appropriate shock and particle velocities in his fluid fracture experiments, are in good agreement with the calibration curve, except for his point at 6.7 kbar. We can reach no meaningful conclusions regarding the large deviation of Keough's data from the calibration curve until we can carry out a group of systematic experiments using foils and films embedded in glass or ceramic insulators.

Figure 8 shows the difference between the curve associated with the data points from lot 068 and that associated with the other three lots. As was pointed out previously, the difference in the two curves was found to be statistically significant. An F-test was made of the hypothesis that there was no difference between lot 068 and the others taken together and an F-ratio value of 4.82 was obtained. Under the null hypothesis assumption of no difference between lot 068 and the other three together, the probability of obtaining a value this large or larger is less than 1% (i.e., the difference is significant at the 1% level). Since this difference in loading behavior, as well as those in resistivity and hardness could be attributable to differences either in chemical purity or metallurgical history, or a combination of the two, it is not possible to construct a valid explanation for this phenomenon at this time.

An interesting feature of the calibration curve in Figure 7 is the value of the piezoresistance coefficient at very low stresses (below 1 kbar). Keough (1970) has shown that the resistance change under stress with one-dimensional strain (the normal shock conditions) should be larger than the resistance change during hydrostatic, three-dimensional strain experiments. The present work shows the resistance change to be approximately 3% at one kilobar, whereas typical hydrostatic values (Lilley and Stephens, 1971) are about 6% at one kilobar. An examination of the gage configuration employed in our experiments shows that at least a mixed one-dimensional and two-dimensional strain condition probably exists in our gages during the recording period because the width of the active element is not sufficiently greater than the thickness of the foil. It is not possible at this time to specify the exact state of strain obtained in the foil as a function of time and analyze this problem in detail, but the absence of pure one-dimensional strain might partially explain the difference between what we measured and what one would expect from Keough's analysis. This subject is also discussed by Barsis, Williams, and Skoog (1970).

The measured resistivity values contained in Table 2 show that three lots of ytterbium had the same resistivity (within experimental error) as is given by various handbooks (Simons, 1967). While the resistivity of the deviant lot (068) was approximately $5\mu\Omega\text{-cm}$ greater than that of the others, the foil from this lot was also harder than foil from the only other lot whose hardness we were able to measure.

Temperature-resistance data for the ytterbium used in this investigation are shown in Figure 6. It can be seen that the slopes of the 094D and 095D lines are approximately equal, and the slopes of the 068 and 064D lines are smaller and again approximately equal to each other. These data were obtained so that we might attempt to separate thermal and mechanical contributions to the piezoresistance coefficient, and to see if one might expect large differences among lots in loading or in release due to variations in $\Delta R/R_0$ with temperature. As can be seen, the maximum difference at 60°C would be less than 0.6% of R_0 .*

* All of these numbers are corrected to compensate for the fact that the temperature-resistance data do not all start from the same temperature.

(1971) have calculated the approximate temperature one might expect for ytterbium shocked to various stresses up to 35 kbar. At 5 kbar, the calculated temperature rise is about 10°C , corresponding to a response difference between lots 068 and 094D of 0.2% of R_0 . Since $\Delta R/R_0$ for 5 kbar is shown in Table 5 to be about 42%, the maximum possible temperature-dependent difference is about 0.5% of the total fractional change, which is negligible. Also, the temperature rise noted cannot account for any major part of the unloading hysteresis observed. For example (again using Lilley and Stephens' calculations) if we unload from 4 kbar, we have found the zero-stress residual resistance to be about 7% of R_0 , whereas the final temperature predicted by Lilley and Stephens would be less than 5°C above the original temperature, giving a maximum final thermal $\Delta R/R_0$ of less than 0.5% of R_0 . Interpretation of these data are not entirely straightforward because the shock temperature of the ytterbium is not necessarily the same as the shock temperature of the surrounding material, and the temperature reached by the gage will also depend on the amount of heat transfer that takes place between the gage and the encapsulator and on the direction of the transfer.

Figures 9 and 10 show the zero-stress residual resistance ($\Delta R/R_0$) plotted versus peak stress in two different ways. In Figure 9 it is plotted as it is usually, and in Figure 10, it is divided by the peak resistance change ($\Delta R/R_0$) giving $\Delta R_H/\Delta R$ and then plotted against peak stress. Ordinate and abscissa have been interchanged between the two figures so that certain features can be emphasized.

Figure 9 shows that the residual resistance after shocking does not seem to be a linear function of peak stress. No single one of the four lots of ytterbium seemed to show significantly more or less residual resistance. The most interesting feature is that the curve does not seem to extrapolate to $\Delta R_H/R_0 = 0$ at zero stress, but rather at some stress on the order of 1 kbar, which is what we might expect to be a reasonable value for the Hugoniot elastic limit of ytterbium.* This

* This assumes a purely one-dimensional strain state in the gage.

suggests that the unloading behavior could be affected by irreversible yield point phenomena. We were not able to test this hypothesis because all of our data points at stresses below 1 kbar were obtained by double shocking, and since there often does not seem to be a residual resistance after the second peak in any double-shock experiment, we cannot yet conclude that zero-stress residual resistance after subkilobar shocks is nonexistent.

The results depicted in Figure 10 show that there is a maximum in the $\Delta R_H / \Delta R$ curve which occurs at approximately 4 kbar. This is not surprising when we look at the loading curve in Figure 7 and at Figure 9. The loading piezoresistance coefficient begins to increase markedly in the vicinity of 1 kbar where it becomes constant at least up to 7.8 kbar, while the residual resistance per kilobar peak stress is decreasing in this range. If we divide one function by the other, we would expect a curve with a maximum in it. If nothing else, this result suggests that residual resistance as a percentage of original resistance ($\Delta R_H / R_0$) is a better parameter to use than residual resistance as a percentage of peak resistance change ($\Delta R_H / \Delta R$) when describing this phenomenon. In addition, the presence of a maximum in the curve of Figure 10 raises the possibility that some of the irreversible effects that might contribute to the zero-stress residual resistance (such as defect production) might begin to saturate at approximately 4 kbar or below.

Figure 11 contains calibration curves for states reached after unloading from peak stresses of 4.02, 2.58, and 1.28 kbar. These curves were obtained by comparing our resistance-time records with stress-time records generated by a modified SWAP-7 (Barker, 1967) computer code. The input to the program consisted of (a) the physical dimensions of our targets, (b) the impact velocities, and (c) the equation-of-state data for plexiglas presented by Barker and Hollenbach (1970). A typical SWAP-7 stress-time output is shown in Figure 12. Because SWAP-7 approximates rarefaction fans as a series of waves, the release portion of the curve appears as a step function rather than a continuously decreasing function of time.

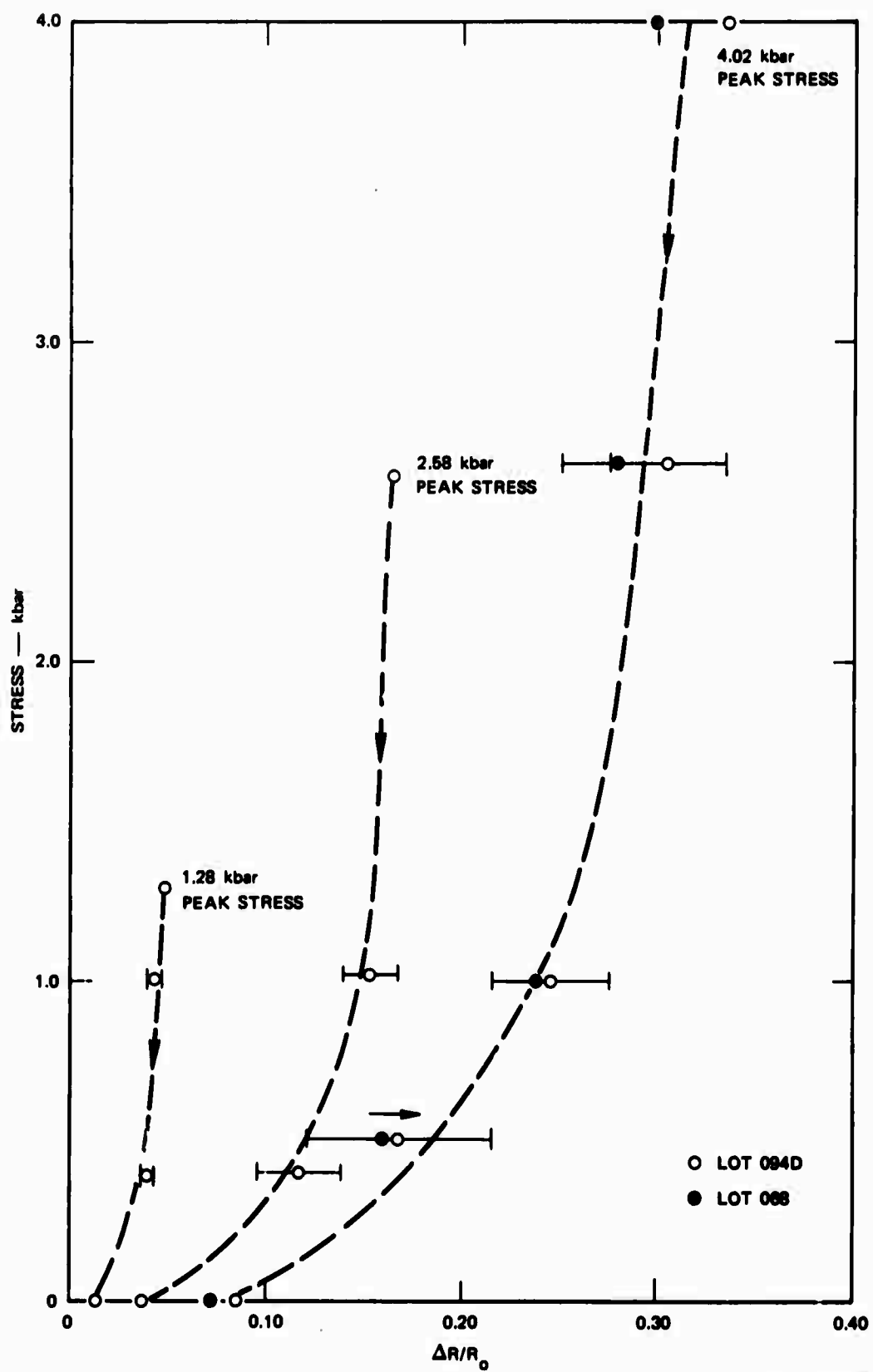


FIGURE 11 UNLOADING STRESS-RESISTANCE DATA FOR YTTERBIUM FOILS IN PLEXIGLAS

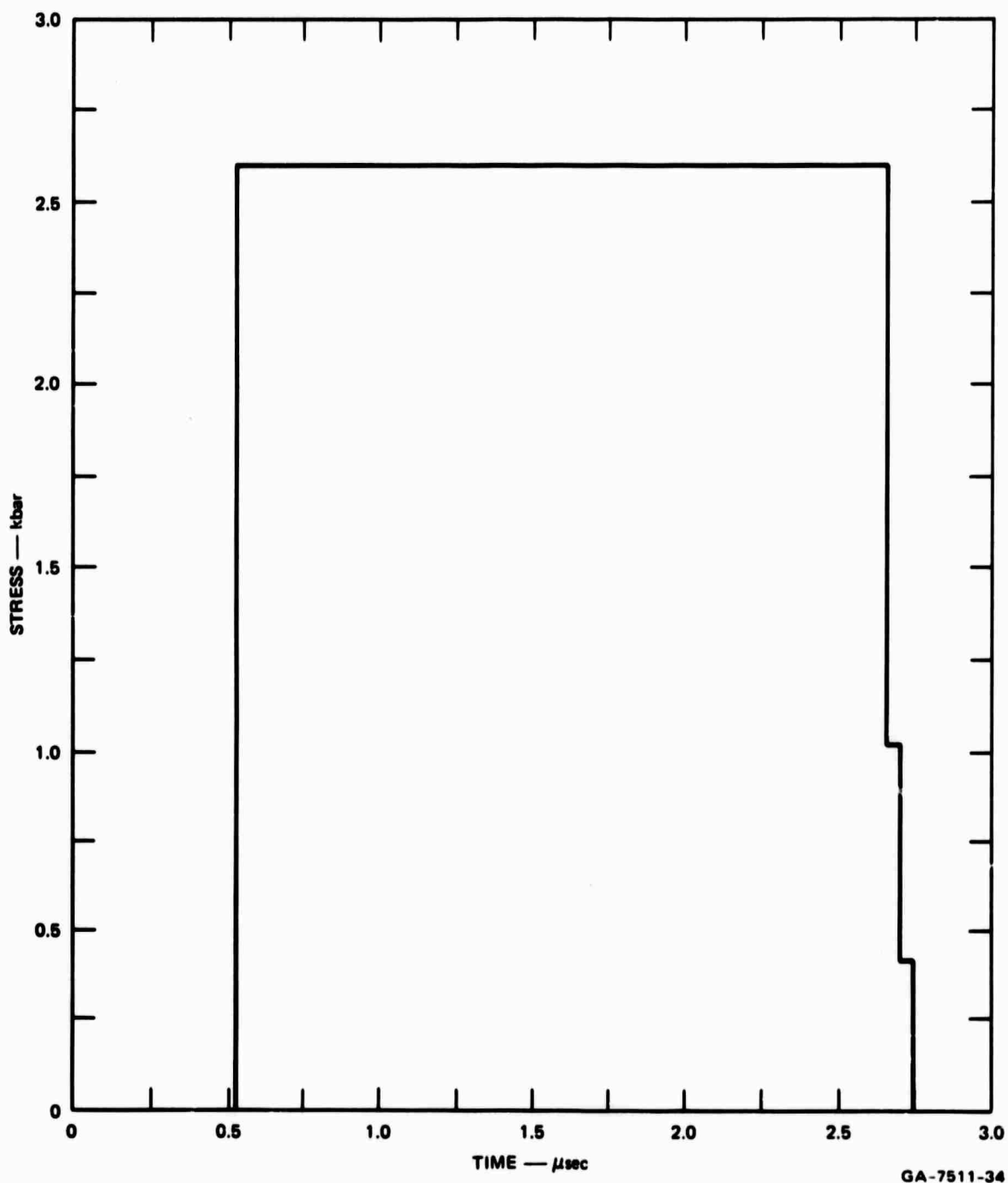


FIGURE 12 SWAP-7 STRESS-TIME OUTPUT

To plot the curves in Figure 11 the arrival time obtained from the computer output was normalized to the actual gage record, and a resistance value was obtained for both the maximum and minimum time at each step. These resistances were then assigned to the stress associated with the particular step, and the spread taken as the error for each determination. It can be seen that the unloading paths deviate markedly from the loading path and are not linear. Each of the curves seems to be steep and linear at the beginning of release, with increasing curvature toward the loading path as zero stress is approached.*

This particular type of behavior complicates attempts at determination of stress histories during the release portion of a low-peak-stress dynamic process. If, for example, we are determining the unloading path of a material which has been at a peak stress of 4 kbar, our gage would register only a small resistance change (about 3% of R_0 or 10% of the overall change in $\Delta R/R_0$) while the stress has changed from 4 kbar to 2.6 kbar. However, once the curvature of the release calibration curve increases, the situation improves considerably. For example, between about 1 kbar stress and zero stress, the resistance decreases by approximately 16% of R_0 or about 66% of the instantaneous 1 kbar value of $\Delta R/R_0$. The most important observation to be made here is that the first small drops in resistance from value at the peak stress or subsequent compression pulses can represent large changes in stress, and this portion or these portions of a gage record should be examined in detail because a large part of the important information in the record is to be found there. This also points up the desirability of using high resistance gages in field shots and the need for adequate discrimination between signal and noise.

* No attempt was made to fit these curves to mathematical expressions because of the small number of points included in each curve. It is important, however, that these fits be made as soon as more data are generated so that rarefaction behavior in materials can be studied in more detail.

One can see a qualitative resemblance between the form of these curves and observed dynamic unloading curves for metals plotted in the stress-strain plane. This is not surprising, but is probably not a complete explanation for the behavior shown in Figure 11 , because we know that the major contribution to the observed change in resistance upon loading is the change in resistivity rather than the change in dimensions. A more detailed and sophisticated treatment of both the loading and unloading behavior based on the material properties of ytterbium was not attempted because the primary objectives of this project were to obtain the data we need so that ytterbium can be used with confidence as a dynamic stress transducer. We believe that we are approaching a point where we will be able to offer explanations for some of the behavior observed in this study, and that these explanations will ultimately prove to be of real value.

V RECOMMENDATIONS FOR FUTURE WORK

Our results and the evolving needs for reliable field and laboratory gages suggest that the following areas require further work.

Additional Calibration (8 to 39 kbar +) and Below 1 kbar

We have calibrated ytterbium in plexiglas from 0.7 to 7.8 kbar. If we assume that ytterbium will be attractive for use in some applications where the expected stresses are greater than 8 kbar, then the calibration should be extended to at least 39 kbar, where we expect a semiconductor → metal transition. Two observations are relevant here. The first is that it has been shown in static work that the 39-kbar phase change is extremely sluggish (possibly requiring minutes or hours). The second is that the pressure-resistance response between 11 and 39 kbar should be more sensitive to impurities than the response between 0 and 11 kbar, because ytterbium is a semi-conductor in this region. The first observation suggests that there is a possibility of using ytterbium above 39 kbar; the second points up the possible need for closer control of materials parameters in this range. In addition, further investigation of the subkilobar response is required using single shock experiments so that better accuracy can be obtained in this range.

Exploration of Behavior in Other Encapsulating Materials and Dependence of Response on Gage Form

It has been shown that the piezoresistance coefficient of a manganin gage often depends on the shock response of the material in which it is encapsulated and on the form of the gage, i.e., wire, foil, or film. The data obtained previously by Keough on the piezoresistance of ytterbium in glass and novaculite differs by up to 100% (in $\Delta R/R_0$ at 5 kbar) from the data obtained in the present work, where plexiglas was employed as the encapsulant.

We believe that it would be useful to compare the results obtained in polymers, in elastic materials, and in metals, and to re-examine the behavior of deposited films. In addition, and most important, we should compare the response of one- and two-mil rolled foils, because some field applications require the extra durability obtained through the use of two-mil foil encapsulated in fiberglass.

Release Behavior

We now feel that there is a possibility of eliminating hysteresis, or at least lessening the magnitude of the effect and making it more reproducible. Since understanding release response is extremely important, we should continue the calibration work and explore some hypotheses concerning hysteresis. Specifically, the amount of hysteresis shown by the gage might depend to some extent on the mechanical history of the material from which the gage is fabricated. Foil which has been cold-worked even more than the foils used in this work might, in the region below yielding or slightly above it, release on paths which are close to the loading paths. In addition, if a large amount of the piezoresistance arises from lattice defects, then introducing an extremely large number of defects before shocking might make the entire loading and unloading process more reversible.

Determination of Dynamic Mechanical Response of Bulk Ytterbium

Some idea of the yield stress and the determination of some loading and unloading paths for different lots of ytterbium would be extremely useful in interpreting our piezoresistance results. The slope change at approximately 1 kbar suggests a yield point effect on the resistance, an effect which should be investigated further. These data would also be of value in determining the amount of hysteresis that arises from irreversible resistivity changes due to the introduction of lattice defects.

Theoretical Work

A number of the phenomena encountered in this work can probably be explained and understood in terms of data now appearing on the electronic structure of ytterbium and its alloys. Application of new concepts and data should be an integral part of any future investigations. Also, the

actual state of stress and strain in the gages while loading and unloading proceeds is not well understood. We now have computer prediction techniques available that will help in providing more insight into this behavior, and we believe that performing such calculations would prove to be extremely useful.

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